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The Nature of Dark Matter¹

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Abstract

The dynamics of the universe may be dominated by novel weakly interacting elementary particles, by baryons in an invisible form, by black holes, and globally by vacuum energy. The main arguments for and against such hypotheses are reviewed.

1 Introduction

On galactic scales and above, the mass density associated with luminous matter (stars, hydrogen clouds, x-ray gas in clusters, etc.) cannot account for the observed dynamics on those scales (Trimble 1987), revealing the existence of large amounts of dark matter (DM) or else pointing to a breakdown of Newtonian dynamics or the conventional law of gravity. The role of DM could be played by anything from novel weakly interacting elementary particles to normal matter in some invisible form (small stars, black holes, molecular gas, etc.). A global, homogeneously distributed DM component can be provided by the vacuum in the form of a cosmological constant. It is attempted here to summarize the main arguments that have been advanced for and against various solutions to the DM problem.

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2 Big-Bang Nucleosynthesis

One of the standard arguments for the existence of nonbaryonic DM is provided by big-bang nucleosynthesis (BBN). In the standard big-bang scenario of the early universe, the primeval abundance of the light isotopes ^2H , ^3He , ^4He , and ^7Li has been produced after the freeze-out of β equilibrium between protons and neutrons (Börner 1992; Peebles 1993). The large number of photons relative to baryons keeps the nuclei in a dissociated phase for a relatively long time after β freeze-out, allowing neutrons to decay freely during that epoch. Therefore, the yield of these isotopes is very sensitive to the number ratio η between baryons and photons. It is noteworthy that η remains the only free parameter of standard BBN after the neutron lifetime and the total number of neutrino flavors ($N_\nu = 3$) have been measured in laboratory experiments with high precision (Particle Data Group 1994). Because the present-day number density of cosmic microwave background (CMB) photons is well measured one can translate η into a value for the cosmic baryon density in units of the cosmic critical density, $\Omega_B h^2 = 0.0037 \eta_{10}$ where $\eta_{10} = \eta/10^{-10}$. Here, h is the present-day Hubble expansion parameter in units of $100 \text{ km s}^{-1} \text{ Mpc}^{-1}$.

BBN must confront two all-important questions: Are the observationally inferred primeval light-element abundances consistent with a single η value? If so, does it imply that some of the dynamical mass of the universe must be nonbaryonic? The answer to the first question is the subject of a renewed debate that has not come to a final conclusion at the time of this writing (e.g. Copi, Schramm, and Turner 1995; Hata et al. 1995).

The most important observational indicators for η are the primeval deuterium (D) and ^4He abundance while ^7Li does not play a particularly decisive role because the BBN predictions as well as the observational data are bedeviled by large uncertainties. The primeval ^4He abundance inferred from metal-poor HII regions is $Y_p = 0.232 \pm 0.003$ (statistical error) with a systematic uncertainty estimated by different authors between ± 0.005 and ± 0.014 . Based on the former, Hata et al. (1995) infer a 95% CL range $\eta_{10} = 1-3$.

The primeval D abundance used to be derived from the local interstellar medium, and from abundance measurements of ^3He together with a chemical evolution model for D and ^3He , the main idea being that all of the D destroyed in stars should show up in the form of ^3He . For example, Hata et al. (1995) infer a primeval D/H number ratio of $1.5-5.5 \times 10^{-5}$ which leads to a 95%

CL range $\eta_{10} = 4.5\text{--}9$ which does not overlap with the helium-inferred η range. On the other hand, recent measurements of D absorption lines in the spectrum of a high-redshift quasar yields a D abundance of around 10^{-4} which correspond to η values consistent with those inferred from ^4He (Songaila et al. 1994; Carswell et al. 1994; Rugers and Hogan 1995). While the D absorption lines, in principle, could be an artifact caused by a hydrogen “interloper cloud” which is located at a suitable redshift, this interpretation may not fit the characteristics of the observed line shape. Confusingly, from D absorption lines in a different quasar system Tytler and Fan (1994) find a low D/H ratio which conforms to the traditional interstellar medium ones.

If the high absorption-line values for D are correct, the ^3He -inferred values must be plagued by unaccounted systematic effects, probably from overly simplistic assumptions concerning the chemical evolution of ^3He . The η value would be consistent with that inferred from ^4He , indicating a low baryon density of $\Omega_B h^2 = 0.004\text{--}0.01$ which would be just right to account for all of the luminous matter, plus some dark baryons to spare, but far from enough to provide all the required dynamical mass of $\Omega_{\text{dyn}} \gtrsim 0.2$. Therefore, most of the cosmic mass density would have to consist of some novel form of matter, probably some weakly interacting elementary particles.

On the other hand, if the low D values are correct, the minimal BBN scenario is only consistent if one appeals to large systematic uncertainties, perhaps in the interpretation of the observational data, perhaps in the details of BBN. There are many ways in which the minimal or standard picture of BBN could be incomplete; anything from decaying neutrinos to inhomogeneous baryon distributions could modify the standard predictions (Malaney and Mathews 1993). While the more conservative extensions of minimal BBN do not seem to allow easily for a large enough baryon density to account for the known mass in the universe, it is impossible to exclude this option if one is willing to espouse a sufficiently radical nonstandard BBN scenario.

In summary, within standard BBN together with current observational data a dominant nonbaryonic DM component is strongly suggested. Still, the correct value of the primordial deuterium abundance remains unsettled so that the consistency of standard BBN is not entirely assured. Therefore, it may be premature to rule out a purely baryonic universe on the basis of BBN alone, especially if the overall matter density is as low as 0.2 or 0.3 of the critical density, a possibility which is suggested by the current best-fit parameters of a Robertson-Walker-Friedmann-Lemaître model of the universe.

3 Candidate Particles and Search for Their Existence

3.1 Neutrinos

If most of the cosmic DM does not consist of baryons, what else can it be? Obvious possibilities are primordial black holes or weakly interacting elementary particles. The latter would need to carry a nonvanishing mass, would need to be stable over cosmological times, and must have been left over from the early universe with the right relic abundance. At the present time, no particle with the requisite properties is known. The most popular conjectures include neutrinos with mass, the lightest supersymmetric particle (probably the neutralino), and axions.

Beginning with massive neutrinos, it is noteworthy that all three neutrino flavors ν_e , ν_μ , and ν_τ must obey the cosmological mass limit $m_\nu \lesssim 30$ eV unless one postulates a fast decay channel beyond what is predicted by the particle-physics standard model. The cosmic neutrino sea should encompass around 100 cm^{-3} neutrinos of each flavor. If one of them had a mass in the 10 eV range it would significantly contribute to DM.

No method is known that would allow one to measure the cosmic neutrino sea, whether or not neutrinos have a mass and whether or not they cluster on galactic scales. The only realistic chance to detect neutrino masses in the cosmologically relevant range is to observe neutrino oscillations. The solar neutrino problem is currently the most robust indication that neutrinos may indeed have masses. With $m_{\nu_\mu}^2 - m_{\nu_e}^2 \approx 10^{-5} \text{ eV}^2$ (MSW solution, e.g. Hata and Haxton 1995) or 10^{-10} eV^2 (vacuum solution, e.g. Krastev and Petcov 1994) all solar neutrino experiments can be reconciled with each other and with theoretical flux predictions. This leaves the possibility open that ν_τ has a cosmologically interesting mass which may show up, for example, in the ν_μ - ν_τ oscillation experiments CHORUS and NOMAD which are currently taking data at CERN (Winter 1995). Certain versions of “see-saw” neutrino mass models indeed suggest that ν_τ should carry a cosmologically significant mass if the MSW solution of the solar neutrino problem obtains.

Of course, other more complicated neutrino mass schemes are conceivable, for example one where the solar neutrino problem is solved by ν_e - ν_τ oscillations (e.g. Raffelt and Silk 1995). Such speculations are nurtured by

the candidate events at the LSND experiment which may be interpreted in terms of $\bar{\nu}_\mu$ - $\bar{\nu}_e$ oscillations with $\Delta m_\nu^2 \gtrsim 0.5 \text{ eV}^2$, and perhaps a favored value of 6 eV^2 (Athanasopoulos et al. 1995). While this interpretation is controversial at the present time (Hill 1995), a confirmation with more data would essentially establish that neutrinos do play a cosmologically significant role.

3.2 Neutralinos

While neutrinos because of their small mass would constitute “hot DM,” a plausible “cold DM” candidate is provided by supersymmetric extensions of the particle-physics standard model. Supersymmetry establishes a symmetry between bosons and fermions so that in nature there should be a fermionic partner to every bosonic degree of freedom and vice versa. Supersymmetry is not realized among the known particles so that one predicts the existence of a novel partner for every “normal particle.” They and supersymmetric ones differ by a quantum number known as R-parity. If it is conserved, the lightest supersymmetric particle (LSP) must be stable as required for a DM candidate. Supersymmetry is thought to be a necessary ingredient of grand unification theories (GUTs) which seek to unify the electromagnetic, weak, and strong interactions at an energy scale of $f_{\text{GUT}} \approx 10^{16} \text{ GeV}$. The main purpose of supersymmetry in GUTs is to explain the stability of the weak interaction scale ($f_{\text{weak}} \approx 250 \text{ GeV}$) relative to f_{GUT} , and both relative to the Planck scale ($1.2 \times 10^{19} \text{ GeV}$). This is possible only if the masses of the supersymmetric particles are below about f_{weak} so that their discovery is within the reach of current and near-future particle accelerators.

A favored LSP that would double as a suitable DM candidate is the neutralino, a linear combination of the supersymmetric partners of the photon, the Z^0 gauge boson, and the Higgs particle, which go by the name of photino, zino, and higgsino, respectively. The neutralino’s phenomenological properties are closely related to those of neutrinos. One may think of a neutralino as a Majorana neutrino (it is its own antiparticle) which interacts slightly weaker than weak. The standard freeze-out calculation in the early universe then yields a significant cosmic abundance if the mass is in the 3–300 GeV range.

The question if neutralinos are the DM of our galaxy can be addressed by direct and indirect detection experiments. In the former one attempts to measure the recoils of target nuclei hit by a galactic DM neutralino. The ex-

pected event rate is very small (below 0.1 per day and kg detector material). While many efforts to search for this effect are pursued worldwide, two experiments which are currently under construction deserve particular mention. One (Cryogenic Rare Event Search with Superconducting Thermometers—CRESST) is built in the deep underground Gran Sasso laboratory (shielding from cosmic rays!) by a collaboration between the Max-Planck-Institut für Physik, München, the Technische Universität München, and Oxford University. The other (Cryogenic Dark Matter Search—CDMS) is built at a shallow site at Stanford by a collaboration organized around the Center for Particle Astrophysics in Berkeley, California. While in the upcoming round of experiments the numerous free parameters of the supersymmetric models must take on favorable values for neutralinos to actually be detectable, it is noteworthy that these experiments for the first time have a plausible chance of finding supersymmetric DM.

Neutralinos can be trapped in the Sun and Earth and annihilate there. The annihilation products involve high-energy neutrinos which may be measurable in the upcoming Cherenkov detectors AMANDA, DUMAND, NESTOR, and Superkamiokande. Depending on details of the assumed supersymmetric model, this “indirect method” may beat the direct search experiments to the discovery of neutralinos.

For a detailed review and references concerning supersymmetric DM and methods for its detection see Jungman, Kamionkowski, and Griest (1995).

3.3 Axions

Within quantum chromodynamics (QCD), the standard theory of strong interactions, the neutron is expected to carry an electric dipole moment of roughly the same magnitude as its magnetic one, while it is measured to be at least a factor of 10^{-9} smaller. Because an electric dipole moment for any fermion would violate the symmetry between particles and antiparticles (CP symmetry), its unexpected conservation by QCD is known as the “CP problem of strong interactions.” The most elegant solution invokes a new chiral U(1) symmetry (Peccei-Quinn symmetry) which is spontaneously broken at some large energy scale f_a . The corresponding Nambu-Goldstone boson is the axion, a pseudoscalar particle which is closely related to the neutral pion. The axion mass and interaction strength are roughly those of π^0 , times f_π/f_a where $f_\pi \approx 93 \text{ MeV}$ is the pion decay constant. Because

f_a can be very large, axions can be very light and very weakly interacting (“invisible axions”).

In spite of their weak interactions axions are a QCD phenomenon. In the early universe, they would be produced as coherent field oscillations during the QCD phase transitions at $T \approx \Lambda_{\text{QCD}} \approx 150 \text{ MeV}$. They are produced in low-momentum modes, i.e. they are nonrelativistic from the start. Thus, in spite of their small mass they are a cold DM candidate. In typical scenarios the cosmic axion density is found to close the universe for $m_a = 10^{-5} - 10^{-3} \text{ eV}$, roughly corresponding to $f_a = 10^{10} - 10^{12} \text{ GeV}$. In contrast with neutrinos where $\Omega_\nu h^2 \propto m_\nu$ one finds for axions $\Omega_a h^2 \propto f_a^{1.175} \propto m_a^{-1.175}$ so that axions with masses *below* the closure limit are cosmologically excluded. On the other hand, axions with relatively large masses (relatively small f_a values) can be excluded because they would be emitted from stars too efficiently to be consistent with a variety of stellar evolution limits. Therefore, only a narrow “window of opportunity” of roughly $10^{-6} \text{ eV} \lesssim m_a \lesssim 10^{-2} \text{ eV}$ remains where axions could still exist (Raffelt 1990, 1995). Put another way, if axions exist at all, and if the standard picture of their coherent production in the early universe is correct, they must contribute a significant fraction of the cosmic DM. This is a far more radical statement than can be made about neutralinos because supersymmetry may well exist in nature without providing the cosmic DM.

No method has yet been proposed that would allow one to discover “invisible axions” in a pure laboratory experiment. However, galactic DM axions can be searched by the “haloscope” method. The axion’s two-photon coupling allows for the radiative decay $a \rightarrow 2\gamma$, and for the “Primakoff conversion” $a \leftrightarrow \gamma$ in the presence of an external electric or magnetic field which plays the role of the second photon. The conversion of galactic axions with, say, $m_a = 10^{-5} \text{ eV}$ produces microwaves of the same energy. Therefore, if a microwave resonator is placed in a strong magnetic field one can search for the appearance of a narrow line on top of its thermal noise signal. One such experiment has recently taken up operation in Livermore, California (van Bibber et al. 1995) and another one is under construction in Kyoto, Japan (Matsuki et al. 1995). If axions are the DM of the galaxy, this round of experiments has a first realistic chance of finding them, in contrast with two previous pilot experiments.

3.4 Summary

While it is easy to postulate some ad-hoc elementary particle that can serve as a DM candidate, massive neutrinos, supersymmetric particles, and axions have been invoked for other reasons and are thus well motivated. Current and near-future search experiments may well discover these particles either in pure laboratory experiments or in search experiments for galactic DM. It is clear that one cannot truly establish nonbaryonic DM by indirect arguments, no matter how compelling, unless one of the candidate particles with the requisite properties is experimentally discovered. Therefore, the cosmological importance of the DM search experiments, the accelerator searches for supersymmetric particles, and the search for neutrino oscillations cannot be overstated.

4 Search for Dark Stars in our Galaxy

Even though BBN indicates that baryons likely are not all of the DM, it also indicates that likely there are more baryons in the universe than are visible in the form of luminous matter. Therefore, independently of the final solution of the DM problem, likely some baryons must hide themselves in the universe. One obvious possibility is ionized intergalactic gas (Carr 1994). However, baryons may also condense to form nonluminous stars and may contribute to the DM in galactic halos. In principle, stellar remnants (white dwarfs, neutron stars, black holes) and brown dwarfs are possibilities. A number of more or less standard arguments have been advanced that brown dwarfs and perhaps molecular clouds or black holes are the only plausible objects to hide baryons in galactic halos and/or galaxy clusters (Carr 1994).

Small dark stars can be hunted in the halo of our galaxy by the gravitational microlensing technique which relies on measuring the lightcurves of millions of stars in the Large Magellanic Cloud over many years. Two collaborations have observed first candidate events (Alcock et al. 1995; Aubourg et al. 1995). At the present time it is not assured that these events can indeed be attributed to lensing by galactic halo objects. If they were interpreted as such, the small total number of events allows for any interpretation, i.e. that all or practically none of the halo mass is contributed by Massive Astrophysical Compact Halo Objects (MACHOs). Thus, for now the most important

message is that the method works, and that with the collection of more data the MACHO fraction of the halo mass will eventually emerge.

A purely baryonic halo for our galaxy may consist of brown dwarfs which form something like dark globular clusters, and of molecular hydrogen clouds which are yet another form to hide baryons. For various aspects of such a scenario see De Paolis, Ingrosso, Jetzer, and Roncadelli (1995). Better statistics from future microlensing observations will reveal or exclude such a possibility.

5 Black Holes

Black holes are a DM candidate *sui generis* because they may form from baryons, or they may be present in the universe as “primordial black holes.” For the purposes of structure formation, black holes which formed early enough belong to the category of “cold DM.” For stellar-remnant black holes, severe constraints exist which makes them appear implausible as DM candidates (Carr 1994). Primordial black holes seem to be viable candidates, except that the necessary abundance has to be taken on faith.

6 Structure Formation

The impressive isotropy of the CMB reveals a universe that was very homogeneous at early times while the distribution of matter today is very clumpy and structured. It is thought that the universe evolved from there to here simply by the action of gravity, beginning with an initial spectrum of low-amplitude density fluctuations that had been imprinted at some early epoch, possibly during an inflationary phase. It is well known that this scenario, if true, entails very restrictive bounds on the nature of DM.

It is now a textbook wisdom that a purely baryonic universe is incompatible with this scenario if the initial fluctuations were adiabatic so that fluctuations in the baryon density imprint themselves directly on the CMB. If the initial spectrum was of the isocurvature type the case against baryons is strong but not as clear cut. In order to save such primordial isocurvature baryon (PIB) models one must make use of the freedom of choosing an initial power-law index for the fluctuation spectrum, and of choosing a suitable

ionization history of the universe which modifies the CMB characteristics. Even with that much freedom such models are excluded unless one invokes a cosmological term (Hu, Bunn, and Sugiyama 1995). Of course, a cosmological term is now favored by many. However, in essence it constitutes a form of nonbaryonic DM on a global scale, thus removing the main appeal of the PIB scenario which involves only one form of DM without the need to explain fine-tuned relative abundances of several components.

Even simpler structure-formation arguments exclude neutrino DM. Because neutrinos with $m_\nu \lesssim 30$ eV stay relativistic until about the radiation decoupling epoch, they can stream freely over large distances (“hot dark matter”—HDM). Thus they wash out any previously imprinted density fluctuation spectrum on small scales. With any plausible initial fluctuation spectrum HDM is excluded except, perhaps, in a scenario where structure is formed by cosmic strings or other primordial topological defects.

Apart from structure formation, neutrinos also have problems with small-scale DM. A textbook argument involving the phase space of galactic halos as well as Liouville’s theorem shows that $m_\nu \gtrsim 30$ eV is required for neutrino DM in a spiral galaxy like our own. For dwarf galaxies, something like $m_\nu \gtrsim 100$ eV is needed, in contradiction with the cosmological mass limit.

Weakly interacting particles that became nonrelativistic early (“cold dark matter”—CDM) fare much better with regard to structure formation. Neutralinos, or more general “weakly interacting massive particles” (WIMPs), as well as axions fall into this category. The simplest CDM models have the opposite problem of HDM in that they cause too much clumping of matter on small scales. There are a variety of solutions to this problem. The initial fluctuation spectrum may be slightly “tilted,” i.e. not exactly of the scale-invariant Harrison-Zeldovich form. Or there may be a small admixture of neutrinos—a mass of $\sum m_\nu \approx 5$ eV seems to be ideal, especially if it distributed equally among two or three flavors (e.g. Pogosyan and Starobinsky 1995). Perhaps the most straightforward solution is a model where CDM does not close the universe; it may be open, or it may be critical by virtue of a cosmological term.

In summary, all conjectured DM candidates have problems with some structure formation arguments. For now it looks as if for CDM these problems are the least severe, or most easily patched up. Evidently it is not known if a patched-up CDM cosmology or some completely different physical scenario represents our universe.

7 Cosmological Constant

Vacuum energy of quantum fields can play the role of a cosmological “constant” Λ which is then really interpreted as a dynamical variable. Thus it is possible that Λ , while it is small or vanishing today, was large in the very early universe and thus drove a de Sitter expansion (inflation). In this scenario Λ must have evolved dynamically to its present-day value. Its smallness remains unexplained, and no compelling reason is known why Λ today should be exactly zero (Weinberg 1989).

Inflationary models of the universe have many virtues (Börner 1992; Peebles 1993). However, barring fine tuning they predict a vanishing spatial curvature today which is not compatible with the measured values of other cosmological parameters unless something like 65% of the present-day cosmic energy density resides in the Λ term (Ostriker and Steinhardt 1995). On a global scale DM may well consist of vacuum energy!

This hypothesis cannot be tested in the laboratory, but only by a careful assessment of the parameters that characterize the Robertson-Walker-Friedmann-Lemaître models of the universe. Of particular importance is a determination of the deceleration parameter—see Carroll, Press, and Turner (1992) for a review, and Ostriker and Steinhardt (1995) for more recent references. A serious theoretical prediction for the present-day value of Λ , and notably if it has to be zero after all, likely must await the emergence of a true quantum theory of gravity.

8 Alternatives to Dark Matter

The hypothesis of particle DM requires nontrivial extensions of the particle-physics standard model. Thus it may seem no more radical to modify general relativity (GR) such that there is no need for DM. In one phenomenological approach (Modified Newtonian Dynamics—MOND; for a review see Milgrom 1994) gravitational accelerations a below a certain limit a_0 are given by $a^2/a_0 = G_N M/r^2$. With $a_0 \approx 1 \times 10^{-8} \text{ cm s}^{-2}$ this approach is surprisingly successful at explaining a broad range of DM phenomena related to dwarf galaxies, spiral galaxies, and galaxy clusters (Milgrom 1994, 1995). Unfortunately, MOND lacks a relativistic formulation so that it cannot be applied on cosmological scales.

One covariant alternative to GR is a conformally invariant fourth-order theory (Mannheim 1995). In the nonrelativistic regime it leads to a linear gravitational potential in addition to the Newtonian $1/r$ term. It explains at least some of the galactic and cluster DM problems.

Before modifications of GR can be taken seriously they must pass relativistic tests. An important case are galaxy clusters where large amounts of DM are indicated by nonrelativistic methods (virial theorem) as well as by relativistic indicators (gravitational lensing, notably giant arcs). Because virial and lensing masses seem to agree well in several cases, scalar-tensor extensions of GR are in big trouble, if not ruled out entirely (Bekenstein and Sanders 1994).

Apparently, no serious attempt has been made to discuss truly cosmological phenomena such as structure formation and CMB distortions in the framework of alternate theories of gravity. At the present time it is not known if a covariant theory of gravity exists that can explain the DM problems on all scales.

9 Summary

Many solutions of the DM problem are on the table, but none is completely convincing. A purely baryonic universe has the advantage that one does not need to invoke hypothetical other components which miraculously have the same cosmic abundance as baryons within a factor of order unity. It is far easier to believe in some mechanism that hides, say, 90% of all baryons in some invisible form, say brown dwarfs, black holes, molecular gas, or an ionized intergalactic medium. In detail, however, a baryonic scenario requires extreme cosmological parameters, large systematic errors in BBN and/or the observationally inferred primordial light element abundances, unmotivated primordial isocurvature density fluctuations, and even then probably a cosmological constant. One way out may be to hide enough baryons in black holes which would effectively constitute CDM. However, the small-scale density fluctuations that might cause the formation of black holes are not well motivated.

A slightly patched-up CDM cosmology fares quite well with regard to structure formation. It is not known, however, if the correct particle-physics candidate is among the ones which are currently favored (neutralinos and

axions). Extensions of the particle-physics standard model allow for the existence of weakly interaction particles with the necessary properties, but do not by themselves demand these properties. Particle CDM can be established only by a direct or indirect measurement of the relevant candidate either in a pure laboratory experiment, or as a constituent of the galactic halo. Several current and near-future experimental efforts are beginning to address this question in earnest.

If a ν_τ mass of, say, 10 eV were discovered in ongoing oscillation experiments, even HDM would have to be taken seriously again, perhaps pointing to topological defects as a cause for structure formation. If more data confirm the LSND claim of $\bar{\nu}_\mu$ - $\bar{\nu}_e$ oscillations, one would be led to believe that a HDM component is what patches up the CDM cosmology.

Modified theories of gravity are able to address some DM problems, but so far no covariant alternative to GR exists that would address all DM problems. Of course, if a convincing such theory would emerge, this sort of explanation of the DM problem would have to be re-assessed.

While arguments involving BBN and structure formation give us valuable and quite compelling hints concerning the possible nature of DM, the question likely cannot be settled without establishing a matter inventory of the Milky Way by direct detection experiments which should turn up the right amounts of particles, baryonic candidates, or black holes.

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